WHY ARE INTENSE GEOMAGNETIC STORMS SO IMPORTANT FOR HUMAN LIFE?

ELENA SAIZ, YOLANDA CERRATO, CONSUELO CID, JESÚS AGUADO
Departamento de Física. Universidad de Alcalá, E-28871 Alcalá de Henares, SPAIN

Abstract: Increasing knowledge concerning the space environment surrounding the earth has become one of the main focuses of research. This is mainly due to the fact that the adverse conditions in near-earth space cause significant damage to technological systems and, consequently, considerable economic losses. Many types of space weather-related anomalies and failings have been identified in recent years, thus converting adverse space weather into one of the threats facing modern human technology. Therefore important efforts should be made to find technical and operational solutions to space weather problems. In this framework, the need to implement reliable real-time warning tools is evident. Meanwhile, the fewer parameters involved in making predictions, the more valuable the tools will be. The present work develops a warning procedure based on the use of the z component of the interplanetary magnetic field only. The aim of this tool is to warn of the occurrence of intense geomagnetic variations, as measured by the geomagnetic Dst index. A comparison of our results with those criteria available in the relevant literature for the occurrence of intense geomagnetic activity shows a significant improvement in alerting capability.

Keywords: Geomagnetic storms – Dst index – Space Weather –Hazards.

1 Introduction

The sun is the star which human life depends on. In quiet conditions solar wind (plasma and magnetic fields travelling together) is constantly blowing off the sun. Solar wind at the earth's orbit has a mean density of about 4 cm^{-3}, a mean velocity of about 400 km/s and a mean interplanetary magnetic field (IMF) of about 5 nT.

However, the sun is an extremely active star and disturbs the earth in several ways. Large solar flares, solar coronal mass ejections (CMEs), or high-velocity solar wind streams occur in the sun from time to time. When this happens, a considerable amount of radiation, highly energetic particle fluxes and magnetic flux is released into the interplanetary medium. Figure 1 offers a schematic representation of the linked sun-earth system.

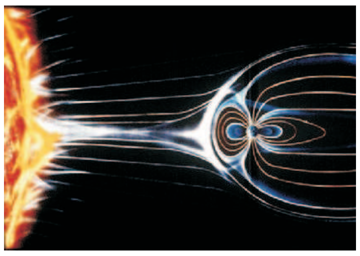

Figure 1: Picture taken from the NASA website showing the linked sun-earth system.

Interplanetary counterparts (ICMEs) of CMEs propagate outward from the sun, often with velocities of up to about 1000 km/s. As they travel faster than normal solar wind, they usually have a shock ahead, a sheath behind the shock with high density and strong magnetic field, and the ICME proper to coherent magnetic field structure.

High-velocity solar wind streams are originated in the solar coronal holes (CHs). As these streams emanating from CHs run into a slower solar wind, co-rotating interaction regions (CIRs) arise.

When these solar events, with different structures, impinge on the earth, major disturbances are detected in the earth's magnetosphere, upper atmosphere and even on the terrestrial surface; in these cases, the solar events are called geoeffective. While the shock, sheath and ICME in CME events are all effective drivers of geomagnetic activity [1], CIR events are also effective drivers but only related to medium-level activity [2].

Solar activity varies in line with the well-known 11-year cycle, a cycle which coincides with magnetic records. ICMEs are more frequent during maximum solar phase and the early part of declining phase of the cycle [3]. However, during the declining phase, where the CHs extend to low latitudes, even reaching the solar equator, CIRs are also significant sources of geomagnetic activity [4].

On the other hand, there are multiple spatial and temporal scales involved in space environment changes. Spatial scales extend from interplanetary medium, outer and inner magnetosphere, ionosphere at high and mid-latitudes up to the thermosphere. Temporal scales go from 1 to 5 days for propagation of solar wind from the sun to the earth, depending on the velocity of the interplanetary structure impinging on the terrestrial magnetosphere; a few tens of minutes for solar energetic particles events; or 8 minutes for electromagnetic radiation. However that may be, the processes, changes, and effects that take place during these important disturbances in the earth's space environment are called 'geomagnetic storms'. Nowadays, their study is of crucial importance, not only because of the intrinsic scientific value they might have, but

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also more practically in so far as they lead to sequences of damage to humans in space as well as to several types of technological systems. Satellites, space-based equipment for positioning and navigation, military reconnaissance, communication and ground-based systems such as electrical power supply networks are all examples of sectors affected by disturbed conditions in space.

The term commonly used to describe the state of the space environment is 'space weather'. COST 724 action, as a contribution to the space weather community, defined that term as follows: “Space weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and nowcasting the possible impacts on biological and technological systems”.

Therefore, space weather involves a chain of events from eruptions on the sun, through propagation of interplanetary disturbances and interaction with the earth's magnetosphere (and other planetary magnetospheres) to their impact on the earth's environment and society. Numerous effects related to space weather have been identified in recent years ([5], [6], [7], [8]). Figure 2 shows the main systems affected when space weather disturbances take place.

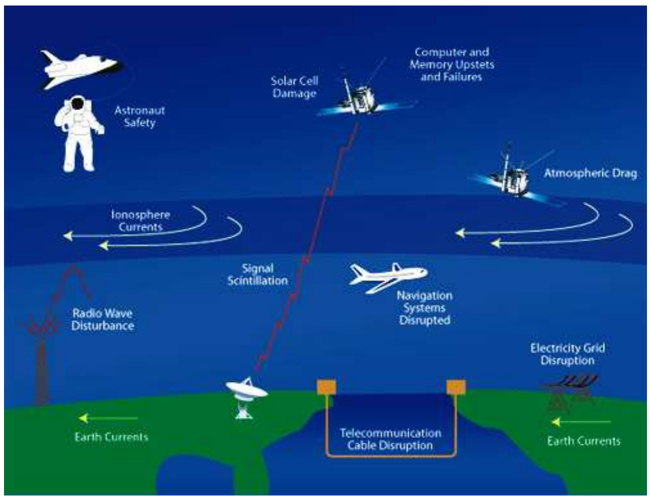

Figure 2: Main systems affected when space weather disturbances take place (taken from the NASA website).

In what follows, a brief overview is offered of the basic properties of the structure and dynamics of the magnetosphere and of the relationships between the drivers and their consequences for both the plasma environment and technological systems.

2 Signatures and effects of geomagnetic storms

The terrestrial magnetosphere is a highly dynamic system controlled by non-linear interactions involving a continuous exchange of energy, mass and momentum between solar wind and magnetosphere, thus driving geomagnetic activity. In 'quiet time' conditions, the solar wind affects the magnetic structure created by the earth itself, distorting the dipolar magnetic field lines. As a result, the magnetosphere is strongly compressed on the dayside (facing the sun) and elongated or tail-like on the nightside. Consequently, the size and shape of the magnetosphere as a whole is controlled by solar wind dynamic pressure. This continuous solar wind-magnetosphere interaction leads to a complicated system of plasma convection flows and currents systems in the magnetosphere, which in turn give rise to its final topology (see Figure 3 for different parts of the magnetosphere).

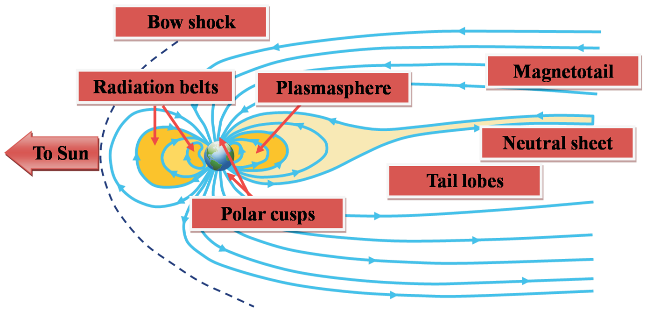

Figure 3: The different parts of the magnetosphere.

When the quiet IMF and solar wind plasma are disturbed by a solar event and impinge on the earth, the bow-shock on the dayside comes closer to the earth as a result of the dynamic pressure enhancement of the solar wind plasma (enhancement in density and velocity). During intense geomagnetic storms, spacecraft in geostationary orbits (6.6 R_E) could be placed outside the magnetosphere in this period of time and suffer serious damage as a result.

Geomagnetic activity is the result of energy entering the magnetosphere, magnetic reconnection being the most important mechanism involved [9]. This process takes place when the IMF and terrestrial magnetic field run in opposite directions. Major geomagnetic activity is recorded when magnetic reconnection takes place at the earth's dayside magnetopause; that is to say, the process is primarily dependent on the southward component of the IMF (B_z) [10]. This scenario may also be described by the dawn-dusk component (E_y) of the interplanetary electric field (IEF) by considering the solar wind as a plasma moving in a magnetic field, and therefore with a motional electric field ($\vec{E} = -\vec{v} \times \vec{B}$).

As a result of reconnection at dayside magnetopause, amount of magnetic flux is carried to the magnetotail where reconnection also takes place with tail-lobes magnetic field lines. As a consequence, the current sheet gets narrower, instability may arise and plasma be released in an explosion and propagated away from the reconnection point.

The plasma heading towards the earth's inner magnetosphere augments the population of the radiation belts and penetrates into high-latitude ionosphere along field-aligned currents (FACs). Because of the gradient and curvature of the dipolar magnetic field, particles trapped in the radiation belts undergo a slow azimuthal drift, constituting the ring current. The increase in the density of drifting particles (of both interplanetary medium and ionospheric origin) during disturbed conditions produces an increase in the ring current ([11], [12]).

In the ionosphere, the present current systems undergo important changes. At mid- and low-latitudes Sq and equatorial electrojet currents exist, mainly generated by heating from solar radiation. At high-latitudes, auroral electrojets are fed by FACs, which connect the high-latitudes ionosphere and the magnetosphere [13]. During geomagnetic storms electrojets are enhanced) by convection flows from the nightside magnetosphere and energetic particles precipitating into the upper atmosphere through the polar regions. As a consequence, there is a higher degree of ionization, which gives rise to an increase in ionospheric currents and temperature, which in turn causes radial outward expansion. The atmospheric drag experienced by Lower Earth Orbiting (LEO) satellites increases, reducing their velocity and causing them to lose altitude, modify their orbit and eventually enter the atmosphere prematurely.

Global positioning systems (GPS) (made up of a satellite fleet orbiting in different planes that cross the outer radiation belt) and terrestrial radio navigation systems may be seriously affected by unexpected changes in charged particle density in the storm-time ionosphere. These changes modify the amplitude and phase of waves, generating distortion and signal intensity fluctuations, as well as gradual power losses, which can lead to loss of communication with the satellite during extreme events.

At high latitudes, solar wind particles can penetrate directly into the upper atmosphere through the polar cusps. Whether by inducing chemical reactions or direct collisions with the atmospheric constituents, precipitating keV-electrons produce excitation and subsequently radiate energy over a broad range of wavelengths (infrared, visible, ultraviolet). This light, called "aurora", can be seen at lower latitudes during geomagnetic storms. Although a pleasing aspect of magnetic storms, these energetic electrons which come into the atmosphere are harmful to spacecraft or aircraft in polar orbits.

Geomagnetically induced currents (GICs) arise on the terrestrial surface as a consequence of magnetic field variations associated with magnetospheric and ionospheric currents. GICs flow in any conducting structure such as electrical power supply network transformers, gas and oil pipelines, undersea communications cables, telephone networks or railways. Moreover, magnetic field variations on their own affect geomagnetic studies for geological surveying, directional drillings, etc.

Solar energetic particle (SEPs) events are a hazard for satellites and space-based instrumentation [14]. If they become trapped in the inner magnetosphere's dipolar field, they populate the radiation belts and reside in the magnetosphere for extended periods [15]. When solar protons with energies in the range of several MeV reach a spacecraft, can penetrate the shielding and bury themselves within dielectric materials. When sufficient charge builds up there can be a powerful internal disruptive discharge, which can affect memory devices and sensitive electronics, causing software and tracking problems. Also, solar panel degradation and power loss may ensue. These solar protons also affect the chemistry of middle and upper atmospheres while colliding with atmospheric constituents: the precipitation of particles lead to an increase of NO_x compounds in the mesosphere and thermosphere, which in turn is a catalyst for ozone destruction. This way solar activity also affects the long-term balance of atmospheric chemistry.

Space weather also has to do with issues of human health. While the terrestrial magnetosphere and atmosphere afford adequate protection for humans living on the surface of the planet, in outer space, astronauts are exposed to dangerous doses of radiation. The penetration of high-energy particles in tissue cells causes genetic mutations, associated with increased long-term risks of inheritable genetic effects and cancer.

3 Monitoring the earth's space environment

Extreme conditions in solar activity, solar wind and geomagnetic disturbances can be observed by a large number of satellites and ground-based sensors. The aim is to know, from all the information available over the longest possible interval of time, what activity levels system operators may expect during geomagnetic storms occurrence and how much warning they need to be given of specific events in order to assess the impact on their systems. In a highly technology-dependent society solar activity and its consequences turn out to play a crucial role.

Any understanding of the intricately interrelated sun-earth system requires monitoring links in the different parts of the chain. In other words, there must be observation of the solar atmosphere, the interplanetary medium, the magnetosphere and the earth's surface if the task of forecasting space weather is to be accomplished.

Solar activity has been routinely recorded by ESA's SOHO mission since its launch in 1995. CME occurrence and their outward direction from the sun is recorded by solar coronagraphs such as LASCO, on board SOHO. Space weather warnings are given for those events that propagate in a direction likely to reach earth.

NASA's twin STEREO spacecraft were launched in October 2006. Their on-board instruments (an extreme ultraviolet imager, two white-light coronagraphs and a heliospheric imager) will provide data enabling analysis of the 3-D evolution of CME from birth on the sun's surface, as well as much improved geometry for ICME. That will allow longer-term space weather predictions.

However, the space weather predictions based only on solar records are not enough because the effects in the near-earth environment are strongly dependent on the orientation of IMF and the velocity of solar wind plasma when encountering the earth. From solar observations alone it is not possible deduce the polarity of magnetic field structure and plasma velocity (unlike plasma velocity near the solar surface) when nearing earth.

Details of storm intensity can be predicted when an interplanetary structure (ICME, shock, CIR, etc.) arrives at the first Lagrangian point distance (L1). There, satellites such as the ACE satellite monitor *in situ* the strength and polarity of the interplanetary magnetic field as well as the density, velocity, and temperature of solar wind plasma. The L1-earth distance makes the prediction from *in situ* data only available about 1 hour in advance.

Another scientific mission whose objective is to monitor space weather from a unique perspective is the Ulysses spacecraft. Its orbit is highly inclined to the ecliptic plane, passing then over the sun's poles. It provides measurements of IMF, plasma, solar energy particles and cosmic rays. Together with the ACE, it enables the evolution of an interplanetary structure to be studied [16].

On the other hand, as solar energetic particle events in the sun impinge rapidly on the earth, the detection of active events with solar X-ray monitors, which routinely monitor the terrestrial environment, provide nowcasts for the space environment.

The terrestrial magnetosphere has been explored by numerous spacecraft orbiting the earth, but direct measurements of the magnetospheric processes during space weather disturbances are limited to a few points in space because the region to be explored is so vast that more comprehensive coverage would require a much higher number of satellites.

Spatial missions like Cluster, launched in 2000 by ESA, are continuously monitoring different zones of the magnetosphere. Cluster is a constellation of four spacecraft in tetrahedral formation with identical instruments on board. The distance separating spacecraft can be changed, so from four point measurements three dimensional vector quantities are revealed (see, e.g., [17]).

From these observational data, precise measurements of the size and speed of the bow-shock, 3D magnetic field topology at the magnetopause, typical spatial scales of high-speed plasma flows propagating from magnetotail to the inner magnetosphere, and the thickness of plasma sheet (obtained using the curlometer technique) have all been obtained for the first time.

Populations such as charged ring current particles and neutral atoms from the plasmasphere are highly sensitive to processes occurring during space weather events such as charge-exchange processes. NASA's IMAGE mission, with its on-board high-energy neutral atom (HENA) imager, monitors the plasmaspheric and ring current dynamics in the inner magnetosphere. This is a clear demonstration that neutral atom imaging is becoming a new tool to monitor the state of the inner regions of the magnetosphere [18].

The geomagnetic activity on the earth's surface is recorded at a variety of ground magnetometer stations. Geomagnetic indices, based on these records, have been drawn up to characterize the variability of the earth's magnetic field, for all its complexity, in a single number.

The AE index measures the horizontal component of the magnetic field at terrestrial surface at auroral latitudes. The signature of geomagnetic activity in the auroral zone, as measured by this index, is an increase of the horizontal component of the magnetic field, reflecting the enhancement of the strength of the auroral electrojet. On the other hand, the Dst index measures the horizontal component of the magnetic field at terrestrial surface at low and middle latitudes. The signature of a geomagnetic storm, as recorded by Dst index, is a large depression known as main phase, followed by a recovery phase when the magnetosphere returns to its quiet state. The geomagnetic storm intensity is classified as moderate, intense or super-intense according to the minimum value of Dst reached during the storm [10]. While the main phase is the consequence of the energy input from the solar wind to the magnetosphere, the recovery phase is the result of the physical loss processes taking place in the ring current associated with neutral particles ([19], [20], [21]).

4 Current state of forecasting intense geomagnetic activity

A useful tool which helps to understand the space weather processes and forecast their potential effects is numerical simulation. From magnetohydrodynamic (MHD) models (using single-fluid description to characterise solar wind-magnetosphere interaction and coupling to the ionosphere), large-scale global MHD simulations have been developed ([22], [23]) to describe magnetospheric evolution. These models provide a large-scale framework for local observations and allow global quantities to be inferred which cannot be obtained directly from observation. However, they are still far for being an accurate forecasting tool.

The first empirical attempt at forecasting was that of Gonzalez and Tsurutani, which searched for the interplanetary cause of intense geomagnetic storms. They found that E_y (calculated as VB_z) greater than 5 mV/m over periods exceeding 3 hours were related to intense storms. It should be noted that this forecasting procedure involves B_z and solar wind velocity. As plasma instruments can be seriously affected by enhanced solar X-ray and energetic particle fluxes, they fail more often than magnetometers; moreover, sometimes the solar wind speed exceeds the upper instrumental limits of plasma detectors. Yet during these events, there is an acute need for a reliable Dst forecast since such disturbances may be accompanied by very large geomagnetic storms. This scenario led Tsurutani and Gonzalez to look for another procedure for forecasting which was not reliant on solar wind velocity. They found that the equivalent magnetic field condition for intense geomagnetic storm was $B_z < -10$ nT, lasting at least 3 hours.

In this section we turn to provide an overview of the ability to forecast intense geomagnetic activity using the previous criteria, that is, to provide hazards of events when the Dst index reaches a value lower than -100 nT, which corresponds to the threshold value required for a storm event to be considered intense [10]. For that purpose, Dst index data provided by the World Data Center for Geomagnetism at Kyoto have been used, while historical IMF and solar wind velocity data from ACE spacecraft have been handled as if they were real-time data. The period covered extends from the spacecraft launch, at the end of 1997, to 2006.

In the first stage, Dst data were analyzed in order to look for those times when the index fell below -100 nT. In an intense geomagnetic storm event, the Dst index is used to show values lower than -100 nT for a few days. Thus, from a forecasting point of view, all those times belong to the same event, of which warning should have been given before Dst fell below the threshold for the first time. A collection of those "first times" is the set of events that a warning procedure should forecast.

The results obtained after using the criterion of Gonzalez and Tsurutani [24] are shown in Table 1, where not only the percentage of hits or misses out of the total number of events are included, but also out of the total number of events for which data was available. Although a data gap will provide a miss hazard, from the scientific point of view only a statistical analysis of available data is acceptable.

	% out of total data available	% out of total data
Hits	49	45
Misses	51	48
False alarms	9	8

Table 1: Results of the statistical analysis of hazards of intense geomagnetic storm events following the criteria proposed by Gonzalez and Tsurutani [24]: $E_y > 5$ mV/m for $\Delta t \geq 3$ h

Table 2 summarises the results obtained after using the criterion of Tsurutani and Gonzalez [25]. In this case, there is no data gap, as this last criterion only involves the z-component of IMF. In both tables, those events for which the forecasting criteria were fulfilled but whose Dst index was over -100 nT are included under the term "false alarm". On the other hand, the term "miss" is used for those events whose Dst index was below -100 nT but for which the forecasting criteria are not fulfilled. Note that the results of both cases are below 50 % of hits, which indicates that a forecasting tool based on the above procedures is not trustworthy for technological purposes.

	% out of total data
Hits	60
Misses	40
False alarms	18

Table 2: Results of the statistical analysis of hazards of intense geomagnetic storm events following the criteria proposed by Tsurutani and Gonzalez [25]: $B_z < -10$ nT for $\Delta t \geq 3$ h

5 Our proposal for warning

The foregoing results encouraged us to look for other features in solar wind that might allow intense geomagnetic activity to be forecasted more reliably. In terms of Faraday's law, it is reasonable to think that fast B_z variations could be the signature of a sudden energy release from solar wind to the ring current, and then of a sharp decrease in Dst index. Figure 4 shows an example which supports this idea.

So, using the same database as in the previous section, we checked the warning capability of Dst index variations below -50 nT in one hour; but this time we took into account a new feature, namely, significant B_z variations over a certain time interval. As this kind of storm, with its rapidly developing main phase, is the most dangerous for technological systems, it is precisely the type of storm space weather forecasting tools should be on the lookout for. Several time scales and thresholds for B_z variations were considered with a view to optimising the warning tool, that is to say, to providing as many hits as possible with the minimum number of false alerts. Different resolution data were also been considered to the same end. The results as a function of the geoeffectiveness of the event are shown in Figure 5.

From just a quick glance at Figure 5 we can deduce that this new B_z signature is more successful than the criteria considered in the previous section, particularly when five-minute resolution data are used. In this case all the geomagnetic storms

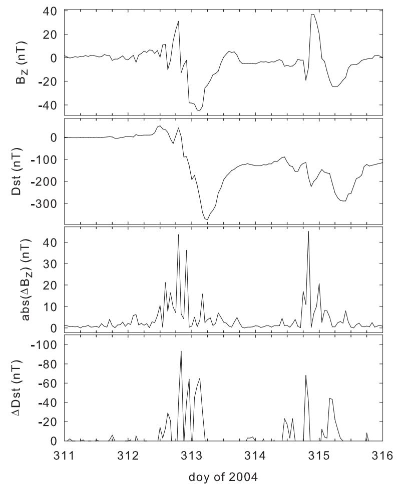

Figure 4: (From top to bottom) Interplanetary magnetic field z- component, Dst index, absolute value of B_z hourly variation and hourly Dst variation for the event happened in November, 2004.

with Dst variations lower than -75 nT in one hour were warned of. Also noteworthy is the reduction in the number of false alarms to only 4 events. As to the number of gaps, it should be noted that the reduction is due to the fact that the warning tool took no account of solar wind velocity data. Moreover, most "misses" showed fast B_z variations between 30 and 40 nT and corresponded to events in which the Dst index varied between -50 and -60 nT. Therefore, it is reasonable to suppose that these misses could be included within the accuracy range of the warning tool. However that might be, our proposal for warning yielded very good results, especially with five-minute resolution data. For this data set, the proportion of "hits" is over 70 %, which represents a major advance in space weather forecasting tools.

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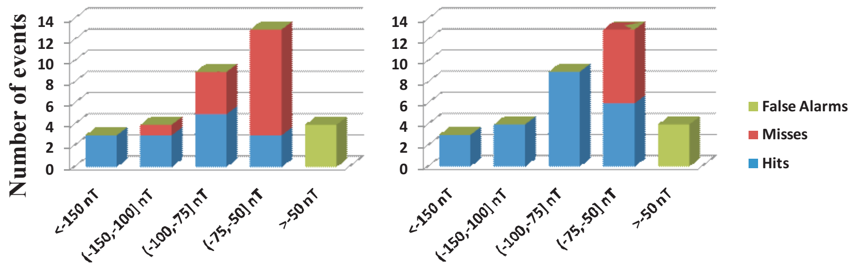

Figure 5: Results of the warning tool as a function of hourly Dst variation using B_z variations at a time interval of 3 hours as a tracer. Left panel corresponds to hourly resolution data, with threshold for B_z variations at 30 nT; right panel corresponds to five-minute resolution data with the threshold at 44 nT.

References

[1] Farrugia, C.J., Burlaga, L.F., Lepping, R.P. 1997, in "Magnetic Storms", Geophys. Monogr. Ser., 98, p. 91, B.T. Tsurutani et al., eds. (AGU, Washington D.C.)

[2] Tsurutani, B.T., Gonzalez, W.D. 1987, Planet. Space Sci. 35, 405

[3] Bothmer, V., Schwenn, R. 1998, Ann. Geophys. 16, 1

[4] Paulikas, G.A., Blake, G.B. 1979, in "Quantitative modeling of magnetospheric processes", Geophys. Monogr., Vol. 21, p. 180, B.P. Olson, ed. (AGU, Washington D.C.)

[5] Lundstedt, H. 1992, "Proceedings of Solar-Terrestrial Workshop", NOAA, 607

[6] Boteler, D. 1993, "IEEE PES Winter Meeting"

[7] Viljanen, A., Pirjola, R. 1994, Sur. Geophys. 14, 308

[8] Lanzerotti, L.J. 2001, "Space Weather effects on technologies", AGU

[9] Dungey, J.W. 1961, Phys. Res. Lett. 6, 47

[10] Gonzalez, W.D., Joselyn, J.A., Kamide, Y., Kroehl, H.W., Rostoker, G., Tsurutani, B.T., Vasyliunas, V.M. 1994, J. Geophys. Res. 99, 5771

[11] Valtonen, E. 2005, in "Space Weather Effects on Technology", Lecture Notes Phys., 656, p. 241, K. Scherer, H. Fichtner, B. Heber et al., eds. (Springer-Verlag, Berlin Heidelberg)

[12] Otto, A. 2005, in "The magnetosphere", Lecture Notes Phys. 656, 133, K. Scherer, H. Fichtner, B. Heber et al., eds. (Springer-Verlag, Berlin Heidelberg)

[13] Devendraa Siingh, Singh, R.P., Kamra, A.K. et al. 2005, J. Atmos. Sol.-Terr. Phys. 67, 637

[14] Baker, D.N. 2000, IEEE Trans. Plasma Sci. 28, 2007

[15] Hudson, M.K., Kress, B.T., Mazur, J.E. et al. 2004, J. Atmos. Terr. Phys. 66, 1389
[16] Rodriguez, L., Zhukov, A.N., Dasso, S. et al. 2007, Ann. Geophys. 25, 1
[17] Escoubet, C.P., Fehringer, M., Goldstein, M. 2001, Ann. Geophys. 19, 1197
[18] Burch, J.L., Mende, S.B., Mitchell, D.G. et al. 2001, Science 291, 1
[19] Jordanova, V.K., Kistler, L.M., Kozyra, J.U. et al. 1996, J. Geophys. Res. 101, 111
[20] Kozyra, J.U., Fock, M.C., Sanchez, E.R. et al. 1998, J. Geophys. Res. 103, 6801
[21] Kozyra, J.U., Jordanova, V.K., Home, R.B., Thorne, R.M. 1997, in "Magnetic Storms", Geophys. Monogr. Ser. 98, B. T. Tsurutani et al., eds. (AGU, Washington D.C.)
[22] Lyon, J.G., Fedder, J.A., Mobarry, C.M. 2004, J. Atmos. Sol.-Terr. Phys. 66, 1333
[23] Hanhunen, P. 1996, in "Environment Modelling for Space-based Applications", ESA Conference Proccedings, SP-392, 233, A. Hilgers, T.-D. Guyenne, eds. (ESA Pub. Div., Nordwijk, Netherlands)
[24] Gonzalez, W.D., Tsurutani, B.T. 1987, Planet. Space Sci. 35, 1101
[25] Tsurutani, B.T., Gonzalez, W.D. 1995, J. Atmosph. Sol. Terr. Phys. 57, 1369